Internet of Satellites (IoSat): An interconnected Space Paradigm

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Abstract

During the last years the space has been populated by Distributed Satellite Systems, which some of them have started to implement Inter-Satellite Communication. However, current solutions are composed of a unique mission and homogeneous spacecrafts or a combination of them. This actually limits their use in the so-called "Federated Satellite Systems" that proposes the interconnection of heterogeneous spacecrafts in order to establish a mission collaboration whenever the resources are not used for the primary mission goal. This point-to-point proposal has some limitations that can be addressed in a multi-hop platform, i.e. a network. Current satellite network proposals, such as Space Internet or Heterogeneous Spacecraft Network, propose the creation of a common network backbone which provides connectivity for future missions. However, this approach supposes huge maintenance and deployment costs. This work presents a new interconnected space paradigm based on a more peer-to-peer architecture: Internet of Satellites. This new paradigm promotes the creation of sporadic networks, called Inter Satellite Networks, which provide the required communication means to deploy Federated Satellite Systems for multi-hop cases.

Keywords

Federated Satellite Systems; Inter Satellite Link; Satellite Networks

1. INTRODUCTION

During the last decades, the space segment has been evolving from monolithic satellites to Distributed Satellite System (DSS). In a DSS the system mission is shared among multiple spacecrafts to improve the performance or making possible new goals. A clear example of a DSS are the satellite constellations, which are a set of spacecrafts placed in the same or different orbit planes, to provide global coverage and/or reduce revisit time.

This kind of DSS is normally conceived as an ensemble of homogeneous satellites that do not interact directly among them, and use the ground segment as a data collector. However, recent research has focused on the introduction of Inter-Satellite Communication (ISC) capability into this kind of DSS. In particular, trying to implement a point-to-point communication, i.e. an Inter Satellite Link (ISL), between two spacecrafts of the same satellite system to improve the mission performance. The Iridium system is a clear example of a first implementation of this new communication type.

Thanks to the existence of these interconnected DSS, new discussions have appeared about the ISC implementation between different satellite systems. One of the resulting paradigms is the “Federated Satellite System” (FSS) [1] which proposes the interaction between heterogeneous satellites in order to establish a win-win collaborative effort between missions. Similarly to cloud computing, this new paradigm is focused on sharing the satellites resources that are not used during their operations, that could be used by others. Establishing a certain similarity, *Uber* has a “fleet” of taxis using the existing capacity of particular vehicles, without owing a single one.

In particular, an FSS can be established between customers and suppliers when a direct link between them exists. These opportunistic links, which represent temporal ISLs, make the communication an important technological challenge. Indeed, the disruptive nature of these ISLs can break a federation when it is active. This implies the limitation of some computing services, such as the memory sharing. In this case, if a data block is fragmented in different packets, some of them can be placed in different suppliers.

This paradigm improves the overall cost efficiency or creates business opportunities, however this point-to-point behavior can limit its capabilities. In order to cope with these limitations, a multi-hop communication platform/network over which federations can be established is needed. Due to the heterogeneity of the satellites, the current ISC solutions do not satisfy these requirements and a new communication paradigm needs to be conceived.

Space Internet [2] and Heterogeneous Satellite Network (HSN) [3] paradigms are conceived to interconnect multiple spacecrafts in order to standardize the communications and reduce the cost of future NASA missions. This initial approach tries to solve this heterogeneity issue by creating an Internet backbone, composed of satellites and ground infrastructure, which provides access to multiple current spacecrafts. NASA Space Communications and Navigation (SCaN) system is the implementation of this paradigm, which provides a scalable integrated mission support infrastructure. However, the deployment and maintenance of this macro infrastructure implies a huge cost and complexity.

For this reason, this work motivates the discussion of a new kind of satellite network which does not use a common network interface. In particular, this new paradigm provides autonomy, flexibility, and scalability in order to develop FSS and other future autonomous satellite applications. The paradigm has been baptized as Internet of Satellites (IoSat) because it is born from the concept of Internet of Things (IoT), which promotes the interconnection of heterogeneous embedded devices using Internet technologies. IoSat aims to sporadically interconnect different satellite systems, creating Inter-Satellite Networks (ISN), taking into consideration intermediate satellite states, goals, and dynamics.

The rest of the work is structured in four Sections: Section II shows the heterogeneity of the current space segment; Section III presents different ISL technologies that could be used for point-to-point FSS and presents its limitations; Section IV details the concept of IoSat and exposes the main difference with current paradigms; finally, Section V presents the conclusions.

2. CURRENT SPACE SEGMENT

The discussion between monolithic and distributed systems has been conducted in multiple engineering domains [4], and space systems is one of them. During these last years, research has focused on the promotion of Distributed Satellite System (DSS) architecture capabilities. In particular, this kind of system is characterized by the fragmentation of mission goals among a set of spacecrafts.

A clear example of a DSS are the satellite constellations, which are a set of spacecrafts placed in the same or in different orbit planes, to provide global coverage and/or reduce revisit time. Different constellations have been conceived for different missions, such as broadband communications constellations. This kind of constellation aims at providing a space communication interface where ground users can establish a connection with remote users. Orbcomm [5] or Globalstar [6] are examples of this kind of constellation, where the interface is based on a relay system. In this case, the satellite becomes a simple repeater between two ground users. This type of solution supposes a big limitation in terms of coverage and communication range. Therefore, a new proposal on satellite communication has been conceived, which is presented in this work.

Specifically, the Inter Satellite Communication (ISC) [7] capability has been largely discussed to improve mission performance. This capability enables the possibility to establish a communication connection between different satellites. A first implementation of an ISC is introduced in the Data Relay Satellite System (DRSS). This system proposes the use relay satellite to forward data from low altitude satellites to the ground segment. Specifically, the NASA Tracking and Data Relay Satellite System (TDRSS) [8] and the ESA European Data Relay System (EDRS) [9] both implement this new satellite system based on relay GEO satellites. These GEO satellites provide an intermediate node to forward data from MEO/LEO satellites. This kind of approach enables improving the data access time because it can be forwarded just after its collection (if a direct view exists). However, the connection between a LEO/MEO satellite with a GEO one can suppose an important resource consumption, impacting on the mission performance. This solution is based on a relay mechanism, which means that there is no concept of route or path.

A new step on the ISC is the conception of an Inter Satellite Link (ISL). This kind of link represents a point-to-point communication between two adjacent satellites. As indicated, this concept is more complex than a relay link because it takes in consideration the link behavior and usage. This kind of communication link has been used in the Iridium constellation [10]. In particular, this satellite system provides voice and data coverage using a set of 66 LEO satellites which are interconnected through ISLs in order to create a mesh architecture. To deploy this architecture, each satellite has two types of ISLs: intra-orbital links (between adjacent satellites of different planes), and inter-orbital links (between two adjacent satellites in the same plane). It is the first time that a satellite system is conceived as a network in which each satellite is interconnected. The forwarding criteria is done hop-by-hop considering the transmission delay, promoting thus routes through high latitudes. This strategy can provoke congestion scenarios at high latitudes, and thus a service degradation. In addition, this scenario works well for this specific constellation structure. Therefore, it seems difficult to be entirely applied in a massive heterogeneous network in which different altitudes and orbital planes are combined.

In particular, Mega Constellation systems are becoming a reality. OneWeb, and SpaceX [11], [12], [13] have proposed to deploy thousands of LEO satellites in order to create a massive constellation which provides global Internet coverage. Although these propositions follow the same specific and close methodology as before, the overpopulation of the space will become a reality, increasing satellite heterogeneity in the space. This makes that satellites with different resources coexist in the same environment, and some of them may not be using their whole capacity. Therefore, a paradigm in which satellites can share resource capacities could improve missions and overall global efficiency.

That is the objective of a Federated Satellite System (FSS) [1] which proposes the establishment of a win-win collaboration between different satellites, i.e. a federation. In particular, a federation is created when satellites coincide and a direct communication (i.e. point-to-point) exists. Moreover, a satellite shall have a need (the customer) which can be satisfied by another satellite (the supplier). Due to orbital dynamics, this collaboration is done following sporadic and opportunistic connections. There is an important difference of this kind of satellite system with respect to the traditional ones: it is a virtual satellite system. Constellations and other systems are physically conceived as a unit and for a unique mission. In a FSS satellites belong to different physical satellite system, but they establish a virtual satellite system whose mission develop the federation which will improve individual missions. It is thus a kind of satellite application which needs a communication interface in order to be established.

3. POINT-TO-POINT FEDERATED SATELLITE SYSTEMS

A point-to-point FSS enables the establishment of a federation between satellites that are in direct view. In this case, a communication link needs to be created in order to deploy the federation. ISL technology is able to create this point-to-point communication link (called FSS ISL) [1]. Using the Open System Interconnection (OSI) model [14], an ISL can be represented by the physical and link layers. Nowadays, it does not exist a unique ISL physical technology that could be used in different satellites. Indeed, this kind of technology directly depends on satellite resources. The discussion on this topic has been focused on trying to determine which solution could be used depending on communication needs. Therefore, a big effort has been done to present a solution map with all the technologies which could work in this context.

An extensive survey on Radio Frequency (RF) ISL solutions for small-satellites is presented in [7]. In physical layer terms, the authors identify that carrier frequency, bandwidth, antenna, modulation, and error correction codes are the most important design parameters that must be addressed. However, due to the strict dependency on satellite capabilities, it is concluded that a standard for a general satellite cannot be defined. Indeed, the creation of multiple standards for each satellite type is motivated.

Although RF is the most common solution, Free Space Optical (FSO) solutions are becoming more and more an object of research for the space segment. A survey on optical communication for ISL is exposed in [15]. It is indicated that the utilization of laser would considerably improve communication bandwidth at the expense of a more accurate attitude control. Considering that this solution has a very narrow beam, the tracking and pointing subsystem becomes essential to establish a direct link, impacting also the satellite attitude control design. For these promising capabilities, there are some projects which try to adapt this optical technology to small-satellites, such as the Steered Laser Transceiver (SALT).

As the physical technology is satellite-dependent, the possibility to use Software Defined Radio (SDR) technology to simultaneously deploy a ground-satellite link as well as an ISL has been evaluated in [16]. It is thus an interesting approach that allows managing technology heterogeneity in a single platform. The experiment has been focused on a RF ISL between two balloons; it would be interesting to translate this technology to a satellite context.

In the link layer context, the main challenge to be addressed is the Medium Access Control (MAC) mechanism. The different mechanisms that can be used in a RF communication are exposed in [7]. In particular, a survey of contention-based and conflict-free protocols are presented. The Carrier Sense Multiple Access (CSMA) in space segment is analyzed as well as deterministic solutions such as Time Division Medium Access (TDMA), Code Division Medium Access (CDMA), and Frequency Division Medium Access (FDMA). The authors highlight that, as in the physical layer, the MAC mechanism is related to the mission objectives, and the number of satellites. For a dynamic and high connectivity environment, CSMA-Collision Avoidance (CA) is the best option to be used, because it offers a distributed non-synchronized mechanism in detriment of collision and band-limited links.

Following the CSMA-CA strategy, an extension of this mechanism with Erasure Correcting Codes (ECC) is presented in [17]. This kind of codes is based on applying a data redundancy on the packet in order to increase reliability point-to-point communication while the number of re-transmissions is reduced.

Considering that satellite segment is an environment with non-negligible propagation time, the combination of both techniques would be useful. In particular, this technique would reduce the number of re-transmissions caused by packet collisions at the expense of a less bandwidth capacity.

Another interesting strategy based on translating entirely current well-known ground technology to space segment is presented in [18]. Specifically, the IEEE 802.11, the IEEE 802.15.4, and the ITU WCDMA 3G standards are evaluated. For satellites which prioritize the link rage, the WCDMA solution would be the optimal one although the data rate is really low. If the need is the transmission rate, the WiFi solution is the chosen one, although it provides low range. It is thus more oriented to high populated constellations. In any case, this strategy is interesting from the commercial point of view because ground technology has largely been analyzed, and its production could be really cheap which make its utilization in the space segment of great interest.

It can be concluded that nowadays the possibility to implement a FSS ISL using state-of-the-art technology exists, although a unique solution for all satellites is still far from being implemented. Instead, as mentioned before, it is tightly related to the satellite design and mission that, in a heterogeneous scenario could be really assorted. Standardization would enhance the compatibility between different satellite systems, and reduce the production cost.

In addition, a point-to-point FSS is strictly dependent on the opportunistic satellite contacts, which could limit its establishment. In particular, the existence of an ISL active time provokes the disruption of created federations. Taking as an example a storage sharing federation, a supplier provides memory capacity to store external data from another satellite. In this case, when the ISL is established the customer performs the data transmission, but when the ISL is broken this transmission is stopped. This situation can provoke a partial storage of the whole data block, creating the customer need to find another storage supplier. Moreover, the sporadic nature of satellite contacts makes difficult to quickly retrieve stored data.

In conclusion, the ISL active time is an important factor that impacts on the federation performance. An analysis of the orbit geometry to improve sporadic ISLs is presented in [19]. It is shown that polar inclination orbits allow having a higher ISL active duration, and thus improving the establishment of federations. However, point-to-point limitations still remain in these situations in which optimal orbits cannot be accomplished. In order to overcome these limitations, the FSS concept needs to be extended to a multi-hop paradigm, i.e. using a satellite network as a communication platform.

4. NETWORKING THE SPACE – INTERNET OF SATELLITES

The extension of the FSS concept over a satellite network would imply the accomplishment of all its benefits in terms of cost, availability, and flexibility. This network can be conceived as a common infrastructure which provides external nodes access to be interconnected, i.e. a network backbone. This is the proposal of the Space Internet [2], and the Heterogeneous Spacecraft Network (HSN) [3], which promote the combination of space and ground system to create a common network backbone which enhances missions.

This approach has been materialized in the NASA Space Communications and Navigation (SCaN) program. In particular, this program defines an architecture composed of three independent networks: the Deep Space Network (DSN), the Near Earth Network (NEN), and the Space Network (SN). The DSN is composed of three specific ground stations oriented to provide communication interface for deep space mission; the NEN is composed of a set of ground stations to provide communication interface for LEO missions; and the SN, also defined as Space Mobile Network (SMN) [20], is composed of the TDRSS, a LEO satellite constellation, and a set of ground stations to provide a mobile satellite backbone for other satellites.

The approach of using a common network backbone can provide the required communication platform over which multi-hop applications can be deployed. However, the deployment of this macro infrastructure implies an important cost, and its maintenance could become a future issue. These limitations can provoke that some mission could not use this infrastructure. An alternative is to conceive this satellite network as a Peer-to-Peer (P2P) scenario, in which private satellites themselves become the network through applications can be executed. Following this idea, a first approach has been presented in [21]. Specifically, it has demonstrated the capability to establish a multi-hop FSS by modeling the satellite network as a Mobile Ad-hoc Network (MANET). However, this proposal does not take in consideration the resource impact and the sporadic nature of an FSS.

One important element in a network is the routing protocol, which is responsible to identify a path between a source and a destination. This process becomes a major challenge due to satellite dynamics, link disruption, and the opportunistic behavior of an FSS. Therefore, traditional network models cannot be simply applied in this context, a deeper analysis shall be done. This is the objective of Internet of Satellite (IoSat) paradigm, promoting the creation of satellite networks following autonomous satellite application nature (e.g. FSS).

The IoSat proposal is focused on defining an interconnected space segment paradigm in order to deploy autonomous satellite applications, such as FSS. In order to manage FSS opportunistic and sporadic nature, the IoSat paradigm does not propose an interconnected space segment based on having a specific backbone infrastructure, indeed it is composed of dynamic, sporadic, and opportunistic satellite networks which are established on collaboration demand.

This opportunistic network, called Inter Satellite Network (ISN), is created thanks to the establishment of multiple federations between intermediate nodes. In other words, the establishment of a FSS between remote satellites is achieved thanks to the combination of intermediate federations, which create an ISN. Indeed, the ISN itself can be considered as a distributed federation in which intermediate nodes play the role of suppliers and customers of packet forwarding service.

Considering that a federation has an activity duration, an ISN follows the same nature, being an opportunistic network with a lifetime (temporal network). This implies that the ISN lifetime is composed of an establishment phase, a maintenance phase and a destruction phase. Moreover, the number of active ISN is totally dependent on the satellite needs to create federations. In other words, different ISN can simultaneously coexist in different parts of the space segment.

Note that an ISN shall satisfy federation requirements, i.e. a memory sharing federation has not the same requirements as a data forwarding federation. Although this requirement heterogeneity, it exists a common need that should be respected in all the cases: the satellite mission. Satellites are embedded systems with severe limitations in terms of energy, computation, and data storage, which means that additional functionalities could impact in the main objective (the mission). As satellites are strictly designed for a specific mission, its participation in an ISN could imply an additional resource consumption. This situation would assume the depletion of the satellite resources, making impossible the execution of the original mission. Therefore, an ISN follows a resource awareness strategy while trying to satisfy application requirements.

Moreover, as a satellite network, the ISN behavior is bound to the satellite movement which makes the network topology highly dynamic, and thus the connectivity is frequently changing. This implies a challenge for traditional solutions and needs to be addressed in order to implement an efficient routing protocol.

The Following table presents a comparison of the major features between current interconnected paradigms with IoSat paradigm.

Table 1 Comparison between interconnected space paradigms

	Space Internet [2]	*Heterogeneous Spacecraft Network [3]*	*Space Mobile Network [20]*	*Internet of Satellites*
Architecture	Backbone	Backbone	Backbone	Peer-to-peer
Heterogeneity	Low	Medium	Low	High
Flexibility	Medium	High	Medium	High
Scalable	Yes	Yes	Yes	Yes
Availability	High	High	High	Low
Maintenance	Complex	Complex	Complex	Autonomous
Deployment	Costly	Costly	Costly	Autonomous

5. CONCLUSIONS AND FUTURE WORK

Last research has promoting the concept of a FSS, that is a virtual satellite system in which satellites establishes a win-win collaboration (federation) to enhance their missions. Initial approaches have been focused on point-to-point federations, which are characterized by service disruption. This work has presented different technological solutions which could be used to implement ISLs for point-to-point FSS. Moreover, it has also been presented the point-to-point limitations to deploy and maintain a federation in this dynamic scenario.

For this reason, the IoSat concept has also been presented. It is a new space segment paradigm in which heterogeneous satellites are sporadically interconnected in order to deploy a communication platform for autonomous satellite applications. In particular, this paradigm promotes the establishment of multi-hop FSS which enhances the limitations of point-to-point scenarios deploying temporal ISN.

As detailed before, this kind of behavior cannot be accomplished with current ISC solutions. Indeed, this dynamic environment implies a major challenge in terms of communication protocols, in particular for routing protocol. This protocol is the responsible to define and maintain a path between a source and a destination. Analyzing nowadays solutions and adapting them to manage this behavior would provide interoperability and interconnection.

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